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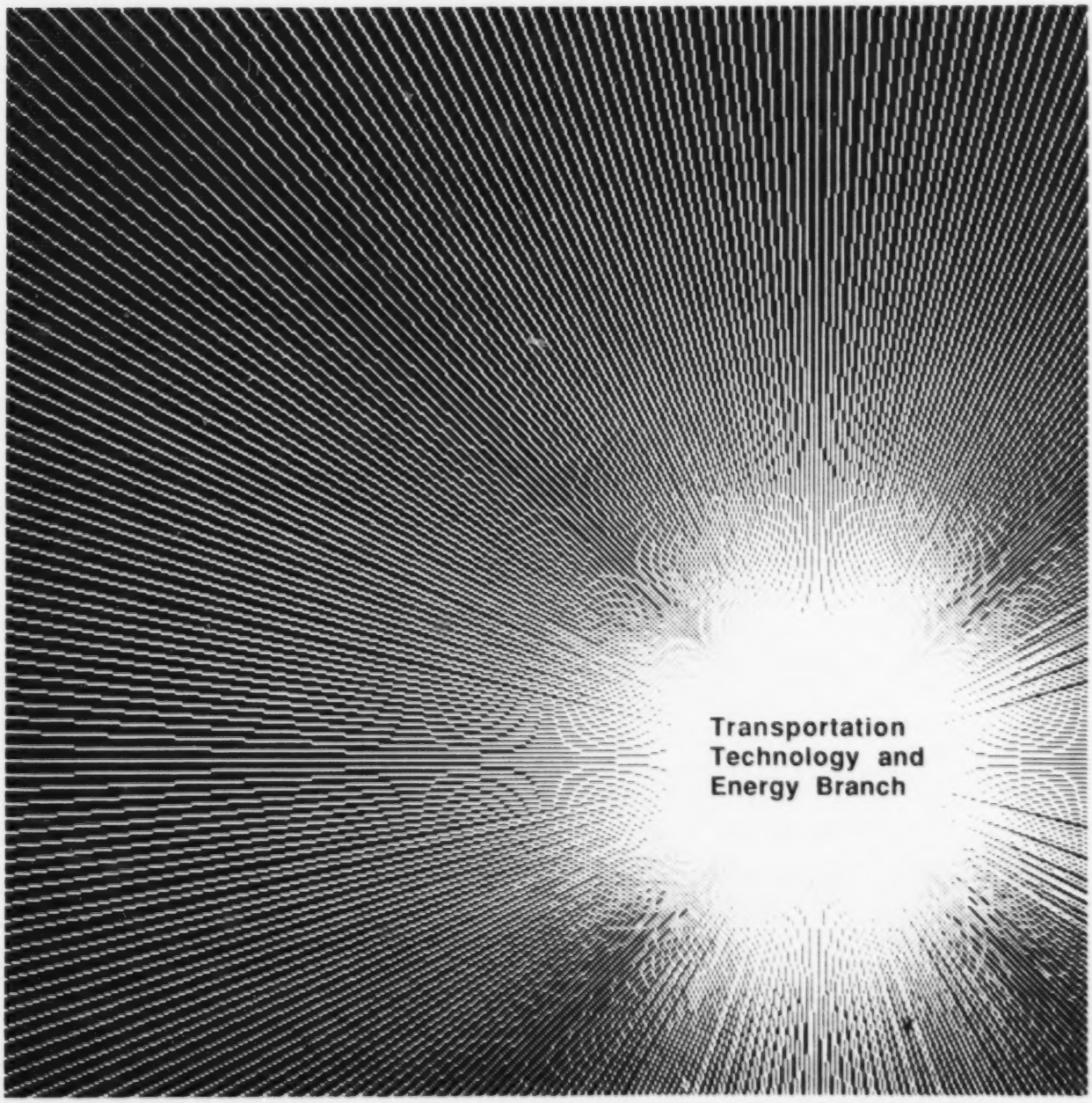

Development and Demonstration of a Class 8 Propane-Powered Truck

AF-90-02

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A paper presented at:
1990 SAE Future Transportation Technology Conference,
August 1990, San Diego, CA. #901499

Also presented at:
The RTAC Annual Conference,
September 1990
St. John's, Newfoundland

Published by:

Transportation Technology and Energy Branch
Ministry of Transportation of Ontario
William Wrye, Minister

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July 1990

Acknowledgements

The authors wish to acknowledge the efforts of Western Star Trucks Inc., Larry's Western Star Inc., and Cummins Engine Company Inc. for their valued contributions to this program.

ABSTRACT

A 261 kW (350 hp) spark-ignited, turbocharged and aftercooled Cummins "Big Cam" propane engine was developed and tested for class 8 truck application. Two propane engines were operated in line-haul service for a total of 33 months and almost 350 000 kilometres (217 480 miles). A diesel-powered tractor, in similar service, was monitored for comparison.

Fuel economy, oil consumption, maintenance, drivers' comments, and engine refinements were fully documented. Propane fuel economy averaged 94 L/100 km (3.0 mpg), relative to 45 L/100 km (6.3 mpg) with the diesel. Overall reliability was good and driver acceptance excellent; however, further refinements, especially in the turbocharger, ignition, and cooling system, are required to compete with the modern diesel.

INTRODUCTION

During the late 1970s, the Ministry of Transportation of Ontario (MTO) formulated a dual approach toward extending the availability of petroleum-based fuels: conservation, and substitution with alternative fuels. Development and demonstration programs were initiated by the Ministry through the early 1980s to promote conservation efforts and provide hardware to enable conversion of light-duty vehicles, as well as trucks and buses, to alternative fuels.

Propane and natural gas were identified as the alternative fuels with the greatest potential in Ontario because of their abundance and indigenous availability at attractive prices.

In 1982 MTO initiated a project to develop a propane engine for heavy truck application. The project was managed by MTO, and funded by the Ontario Ministry of Energy.

FUEL SELECTION

As indicated in Table 1, propane has an energy storage density of 23.6 MJ/L (66% of diesel). Considering the 80% fill limit, propane storage tanks have an effective energy density of approximately 18.9 MJ/L (53% of diesel). Therefore, 90% more volume is occupied by propane than diesel, for a given energy content. Compressed natural gas (CNG), however, requires about four times the volume of diesel for equivalent energy content.

Due to its greater energy density, and because fuel storage space is limited on highway tractors, propane was chosen over CNG for this application. Propane also had the advantage of being commercially available throughout Ontario, unlike CNG, which was available at very few locations.

Propane is currently sold at almost all refuelling stations on the extensive provincial highway network, and at many stations off the highway system. At present, exported propane could fuel more than 10% of the province's vehicles, if diverted to the transportation sector.

SELECTION OF ENGINE

With relatively high octane number, propane lends itself readily to spark-ignition, but not to compression-ignition. Furthermore, the compression-ignition, dual-fuel concept has already been explored [1]. Therefore, the 100% propane (mono-fuel), spark-ignition (SI) concept was selected for this project.

	Propane	CNG	Diesel	Gasoline
Density (kg/L)	.51	.175@	.84	.75
LHV (MJ/kg)	46.3	47.4	42.9	43.8
LHV (MJ/L)	23.6	8.3	36.0	32.8
Price (Cdn$/L)#	.20	.05	.39	.48##
Price ($/100MJ)	.85	.60	1.08	1.46
Octane/Cetane No.	112 RON 97 MON	130 RON* 105 MON*	42 Cetane**	95 RON** 88 MON**

@ - 96% methane at 20.7 MPa (3000 psi)
* - 100% methane
** - typical
# - typical 1990 Ontario price to users with large, private fuel storage facilities
- Toronto bulk price – direct delivered from rack – second quarter 1990

Table 1/ Characteristics of Conventional and Alternative Fuels

A modified diesel engine block was selected to obtain the required displacement, providing adequate power and torque at diesel engine speeds. A diesel engine block would also provide high reliability and minimal installation difficulties. The engine selected was the Cummins NTC in-line six cylinder, which displaces 14 L (855 cu. in.).

	Diesel	Propane
Compression Ratio (:1)	14.5	8.5
Boost Pressure (kPa)	185	55
Boost Control	None	Throttle
Ignition	Compression	Spark
Fuel Metering	Direct Injection	Fumigation
Aftercooler	Air/water	Air/air
Exhaust Manifold	Air Cooled	Water Cooled

Table 2/ Comparison of Propane and Diesel NTC Engines

ENGINE CONVERSION TO PROPANE (PHASE I)

A new engine block was prepared by Cummins Gas Engines. The high compression diesel piston was machined to a shallow dished crown, providing a compression ratio of 8.5:1. No further modifications were made to the engine short block, including the camshaft.

The four-valve-per-cylinder heads were fitted with hardened valve seats and upgraded valves. The fuel injector mounting hole was opened up to accept an adapter tube into which the spark plug was mounted. The adapter tube runs through the valve cover and cylinder head injector hole, incorporating a seal at each of these points (a copper washer at the bottom and an O-ring at the valve cover bore).

The ignition system selected was a Ford "Duraspark" automotive system, incorporating a conventional distributor, single ignition coil, and electronic control module. The distributor is mounted into an adapter block, attached to the rear of the air compressor on the driver's side of the engine (Figure 1).

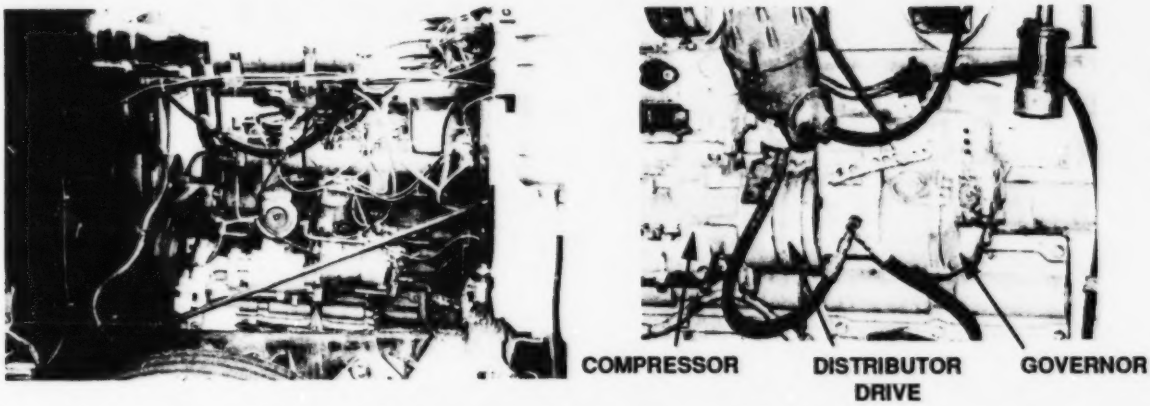

Figure 1/ Propane Engine and Ignition System/Governor Detail

The engine speed governor was a modified Bosch RV mechanical unit, mounted onto the rear of the adapter block, which also drives the distributor (Figure 1). This governor was designed to be driven at camshaft speed (i.e. one-half engine speed). In this application the drive shaft from the compressor turns at 100% engine speed. The situation required modification of governor springs and flyweights. The input lever is connected to the truck accelerator pedal, and the output lever to the propane mixer throttle lever, via solid linkages.

A Schwitzer turbocharger was fitted to the engine in place of the original diesel unit. The new turbo provided boost pressure better suited to an SI engine with a maximum boost of 55 kPa (8 psi), instead of the 185 kPa (27 psi) fed to the diesel. The standard cast iron exhaust manifold was replaced with a water cooled marine manifold, to cool the exhaust prior to its entering the turbine. The primary purpose of the manifold was to protect the turbine wheel from overheating.

Turbo compressor discharge is fed to an Air Research air-to-air aftercooler mounted in front of the radiator. The cooled air is then ducted to the inlet of the propane mixer, mounted on the intake manifold. The mixer is a single Impco 200D unit, fed by two Impco model "E" propane vaporizers. Between the mixer and intake manifold are two throttle plates in series: one connected to the governor output, and the other controlled by the boost control actuator.

A conventional exhaust bypass wastegate was not available for a heavy-duty engine of this power rating. Turbo boost is limited to 55 kPa (8 psi) by an air pressure driven actuator connected to intake manifold pressure, downstream of both throttle plates. As boost pressure in the intake manifold approaches the desired limit, the actuator closes the second throttle plate.

CHARACTERISTICS OF THE CUMMINS PROPANE ENGINE

The Cummins propane engine was set up and tested on an Eaton eddy current dynamometer at ORTECH [2]. Optimum spark advance (MBT timing) over the engine speed and load range was determined (Figure 2). Mixture was adjusted for peak part load efficiency without sacrificing power at full engine load (Figure 3).

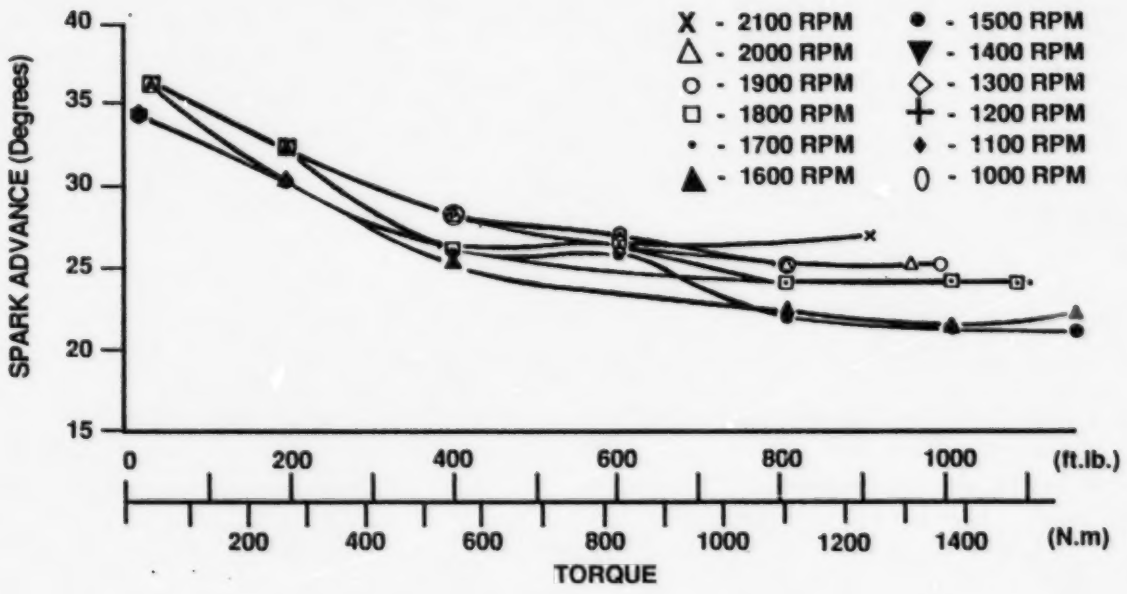

Figure 2/ Spark Advance vs Engine Load and Speed, Ref. [3]

Hydrocarbon (HC) and carbon monoxide (CO) emissions are shown in Figures 4 and 5. CO emission curves indicate lean engine operation at light load, approaching stoichiometric (A/F = 15.6) condition, as load increases. HC emissions are relatively low in the 50 to 150 ppm range.

The brake specific fuel consumption (BSFC) curve (Figure 6) indicates maximum efficiency near full engine load in the 1300 to 1500 rpm range. Peak thermal efficiency of 32% was reached at approximately 1400 rpm.

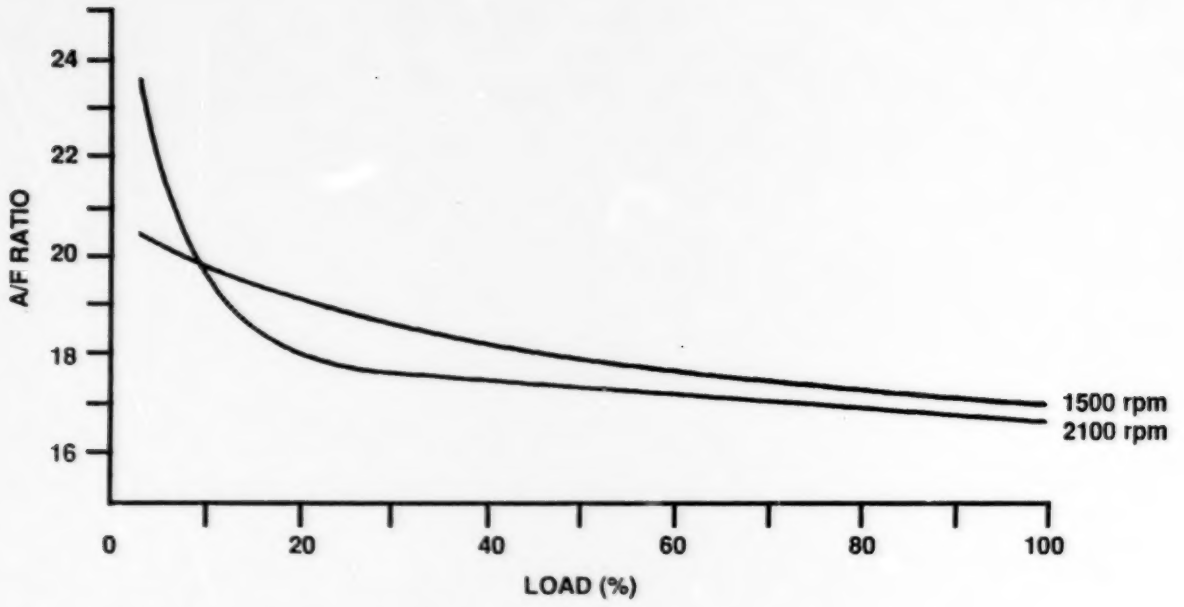

Figure 3/ Mixture vs Load, Ref. [3]

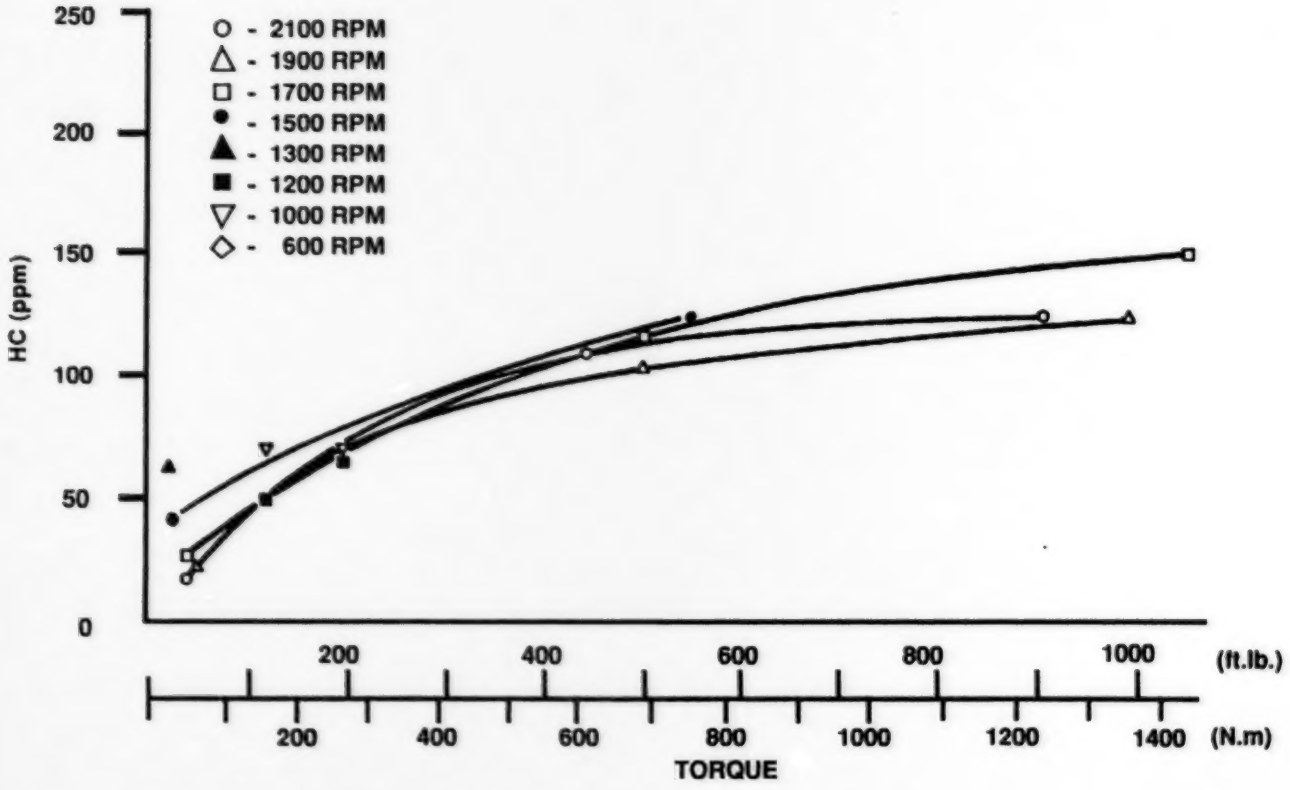

Figure 4/ Hydrocarbon Emissions, Ref. [3]

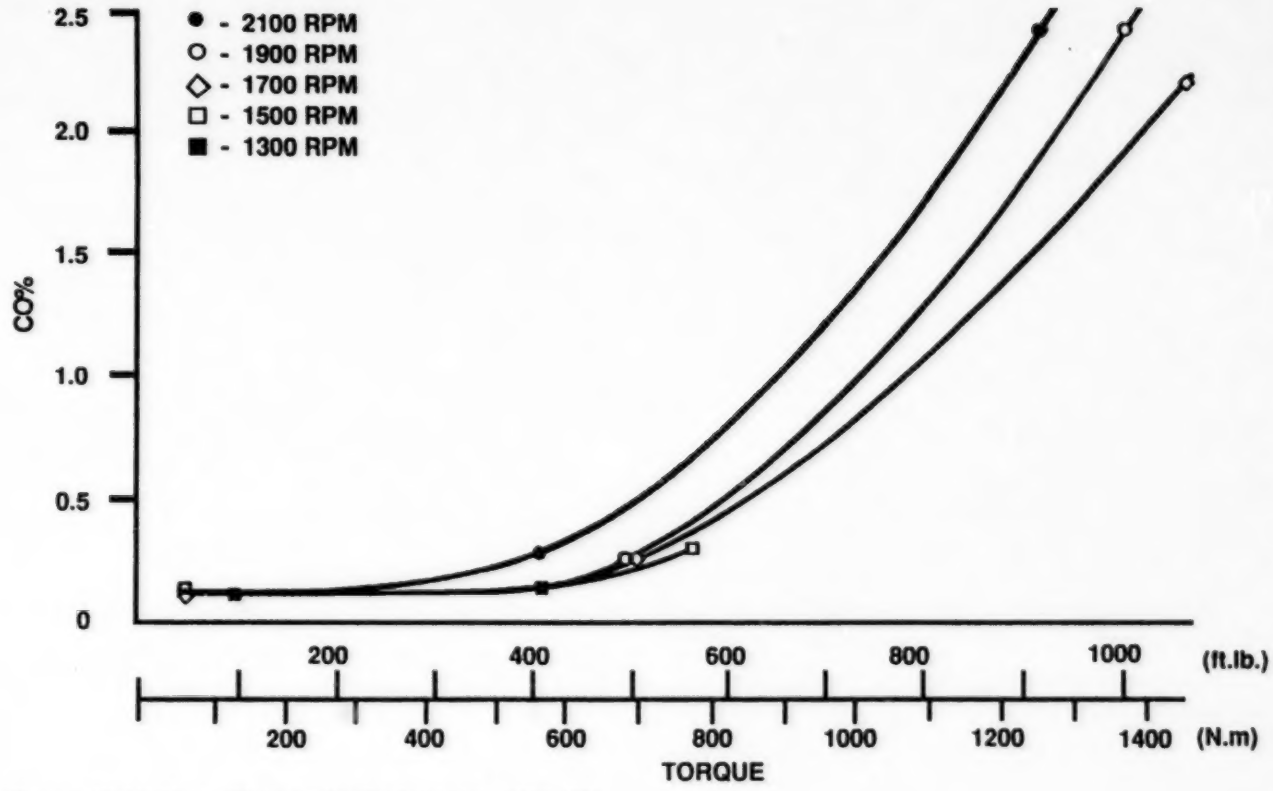

Figure 5/ Carbon Monoxide Emissions, Ref. [3]

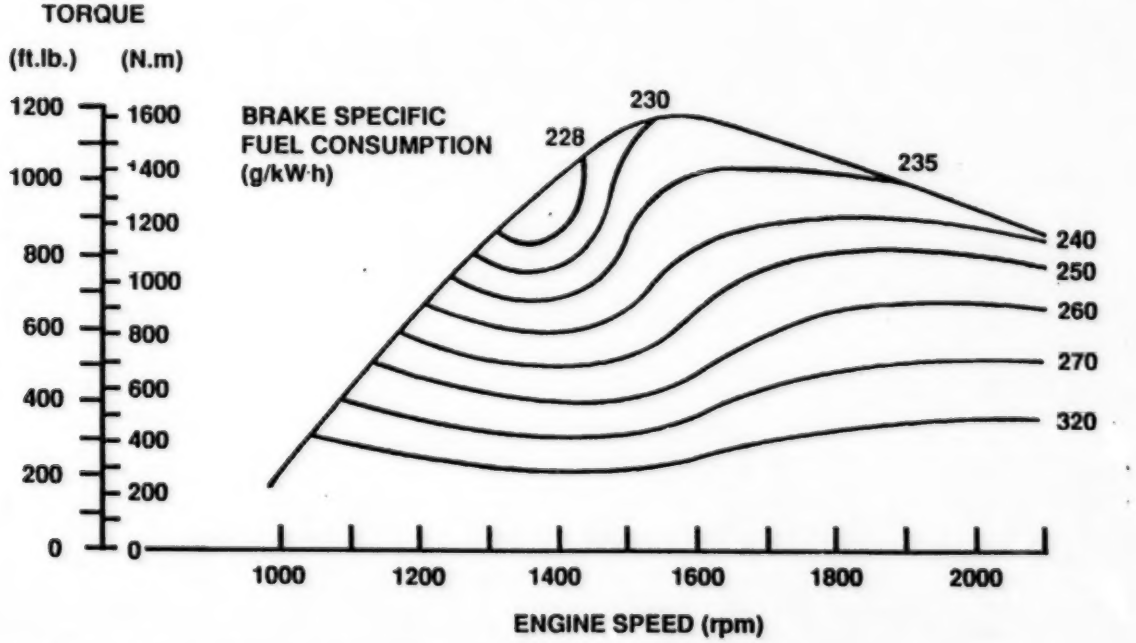

Figure 6/ Brake Specific Fuel Consumption (BSFC-g/kWh)

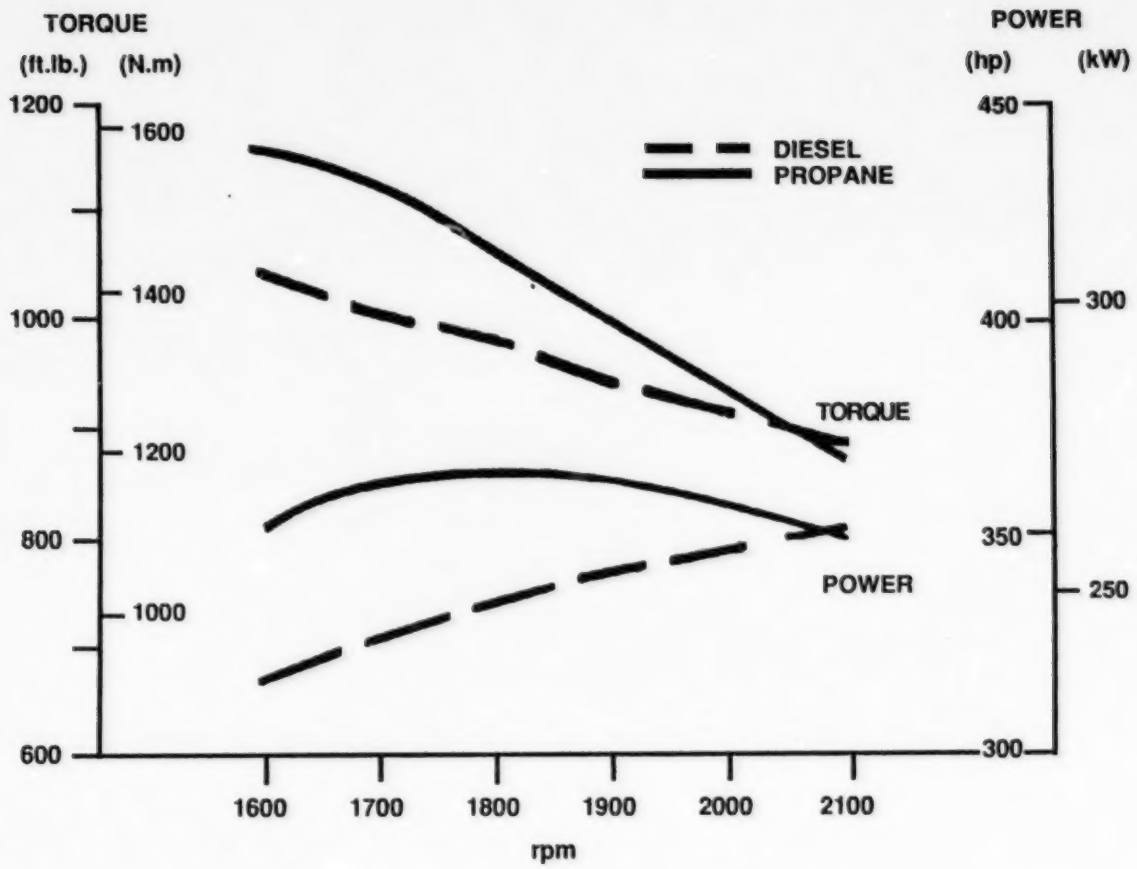

Figure 7/ Power and Torque of Propane and Diesel Cummins Engine

With a rating of 261 kW (350 hp) at 2100 rpm, the propane engine is capable of producing much more power than indicated in Figure 7. To reduce thermal and mechanical stress on the engine, however, the governor was tailored to throttle progressively the engine as speed increased from about 1800 rpm to 2100 rpm. Peak power of 268 kW (360 hp) actually occurs at about 1800 rpm. The resulting torque rise is steeper than that of a typical diesel.

Because of the characteristically shallower pressure rise of the spark-ignition cycle, the propane truck engine was expected to be quieter than the diesel, with lower vibration levels. Longer lube oil life and cleaner combustion chambers were also considered possible, due to the cleaner-than-diesel combustion characteristics of propane.

PRELIMINARY ROAD EVALUATION

After extensive tuning on the dynamometer, the engine was installed in a new (1985) class 8 Western Star tractor (Figure 8). Engine installation was generally straightforward. The radiator end tanks had to be modified to install the aftercooler hoses between the engine and the aftercooler, mounted forward of the radiator. The exhaust system consisted of a simple arrangement from the turbo discharge to a muffler mounted alongside the drive shaft. Exhaust exited directly behind the muffler, since there was no need to eject exhaust above the tractor, as with a sooty diesel.

The tractor was leased by Manitoulin Transport for a period of seven months in line-haul service between northern and southern Ontario. Fuel economy and maintenance records were kept during the evaluation. An overall fuel economy of 107 L/100 km (2.6 mpg) was achieved.

Figure 8/ Propane-powered 1985 Western Star Tractor

The first problem experienced was intermittent backfiring. On one occasion the engine backfired so severely that the cast aluminum intake manifold was cracked, necessitating its replacement. It was suspected that, due to extensive valve overlap, part of the air/fuel mixture could find its way into the exhaust manifold under high turbo boost conditions, resulting in flashback into the intake manifold.

Another problem that was experienced several months into the evaluation was a case of valve sticking. Up until this time, the engine had been operated with a standard diesel engine lubricating oil. It was suspected that the high ash content of the diesel lubricating oil could be contributing to the problem. Low ash oil was used for the remainder of the program, and there were no further incidences of valve sticking.

FURTHER ENGINE REFINEMENT (PHASE II)

At the conclusion of the Phase I road evaluation, ICG Propane Inc. became interested in the concept of heavy-truck propane engines, and entered into an agreement with MTO to further develop and demonstrate the new engine.

The Phase I propane engine was removed from the 1985 Western Star tractor. Cylinder heads and pistons were removed for internal engine inspection. A light soot layer was found on the backs of the valves, however there had been no observed valve or seat wear. All camshaft and crankshaft bearings showed normal wear. Cylinder liners were glazed. The engine was reassembled with new bearings, piston rings, cylinder liners and seals. It was then installed on the ORTECH engine dynamometer for run-in and power check. This work was completed in May 1986.

A second propane engine was also built up and installed on the ORTECH engine dynamometer. This Phase II engine incorporated the following improvements over the Phase I engine:

- a new steel intake manifold designed to minimize internal volume (thus minimizing backfire intensity, related to the quantity of fuel/air mixture contained), and spring-loaded end caps to release manifold pressure, should a backfire occur, and

- a shorter overlap camshaft of 30° CA (crank angle) from the original 54° CA, to reduce the tendency to backfire at higher turbo boost pressure, provided by Cummins Engine Company.

ORTECH also undertook the development of a high compression (9.5:1) piston with a Heron-type cross section. It was felt that the high turbulence developed by the top land of the new piston would enable the engine to run at the higher compression ratio without major changes to the rest of the engine. The higher compression ratio proved to be excessive, however, as the engine could not be run at full load in the 1500 to 1800 rpm range, due to severe detonation. The original 8.5:1 compression pistons were re-installed.

This particular engine was also equipped with a Bosch RQV mechanical governor, which is capable of holding engine speed constant. This governor is specified in power take-off applications, as required by ICG's propane-pumping tractor-trailer configurations.

Finally the engine was mapped to determine optimum mixture and spark advance with the new camshaft and intake manifold, and final adjustments were made to the carburetion and ignition systems. This work was completed in March 1987.

ICG TRUCK CONVERSION TO PROPANE

ICG Propane purchased a new, 1986 Western Star tractor to demonstrate the propane engine technology. The rebuilt Phase I propane engine was installed in the tractor during July 1986. The exhaust system was a typical diesel configuration (dual vertical stacks). Three propane fuel tanks carried a total of 885 litres (195 gallons) of propane (Figure 9). A large 0.935 square metre (1450 square inch) radiator and a direct drive, steel-bladed fan were installed to provide adequate cooling.

Figure 9/ Propane-powered 1986 Western Star Tractor

Figure 10/ Propane-powered 1985 GMC General Tractor

The Phase II propane engine was installed into an ICG-owned, 1985 GMC General tractor in September 1987. This truck had been powered by a Cummins NTC diesel engine, which was due for an overhaul. The conversion included replacement of the diesel fuel tanks with two 318 litre (70 gallon) propane tanks – one on each side (Figure 10).

In April 1988, the Western Star propane engine was upgraded to Phase II configuration with the installation of the new camshaft and intake manifold.

FLEET OPERATION

The two ICG tractors hauled propane tanker trailers from Sarnia to destinations across southern Ontario. Most trips were to the Metropolitan Toronto area, however, many were to points as far away as Sharbot Lake, near Ottawa. Gross Vehicle Weights (GVWs) were typically in the 50-to-55 tonne (110 231-to-121 254 pound) range, over the relatively flat highways of southern Ontario. Trucks were operated six days per week, two shifts per day, with a single driver. The same two drivers operated each rig every day.

A diesel-powered control truck was operated in propane line-haul service on similar routes to those assigned to the propane powered rigs. The truck was a 1987 Mack with a 298 kW (400 hp) Mack diesel engine. Operating data from the Mack were obtained for the period from July 1987 to April 1990. During this time the truck accumulated 500 000 km (310 686 miles).

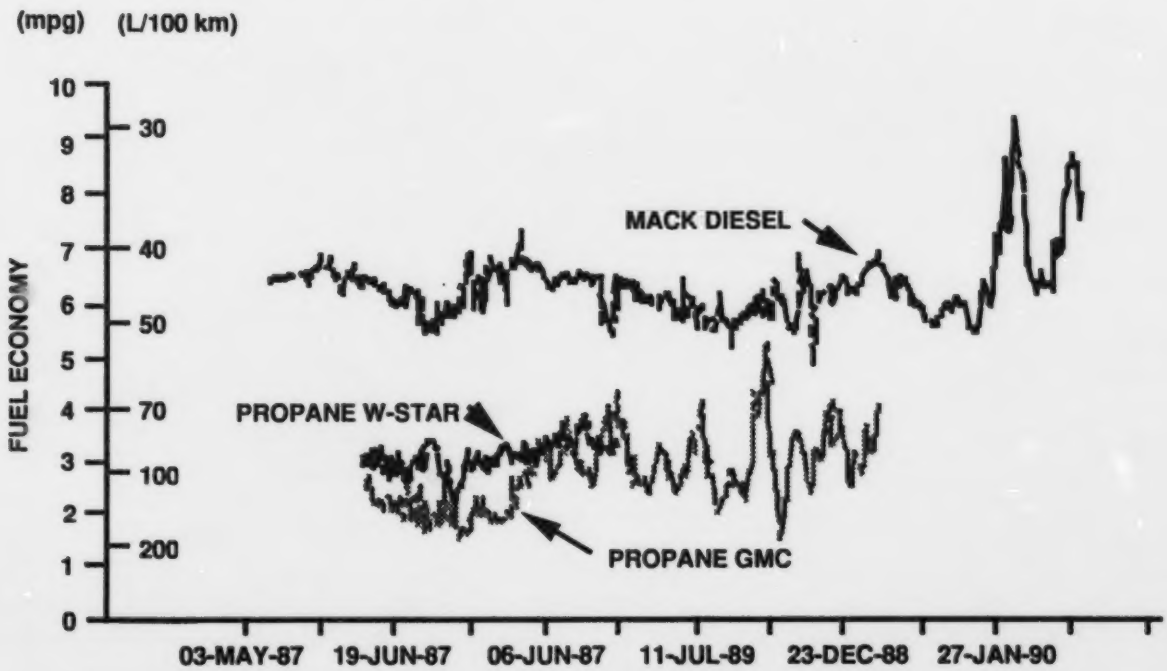

Figure 11/ Fuel Economy of Diesel and Propane-powered Tractors

ICG propane truck drivers completed an operator's report for each shift, in which engine operating information was documented. Shift mileage, fuel, lube oil, and coolant consumption were recorded as well as oil pressure, engine temperature, ambient temperature, and overall condition of the vehicle and engine. There was also a section soliciting the drivers' general comments.

Drivers reported that the tractors were very responsive, with more than adequate power. Because of the steep torque curve, it was observed that grades could be handled one or two gears higher than with a diesel-powered tractor under comparable conditions. They also reported that the propane trucks were much quieter than the diesels, significantly improving their working environment.

Operating information was extracted from the operator's reports, and operating results were tracked continuously. Fuel mileage, mileage accumulation, and lube oil consumption for both tractors were monitored and compared with results from the Mack control vehicle, operating under similar conditions.

Relative fuel economy of the diesel and two propane tractors is shown in Figure 11.

The average fuel economy of the Western Star truck was 91 L/100 km (3.1 mpg) over a total of 158 000 km (98 177 miles); while the GMC averaged 98 L/100 km (2.9 mpg) over 185 000 km (114 954 miles). The average fuel economy of the baseline diesel Mack tractor was 45 L/100 km (6.3 mpg) over a total of 500 000 km (310 686 miles). Based on average fuel economy, and available fuel tankage, estimated ranges of the propane tractors were 982 km (610 miles) (Western Star) and 652 km (405 miles) (GMC). Estimated range of the Mack was 2205 km (1370 miles) based on fuel tankage of 1000 litres (220 gallons). Operating results are summarized in Table 3.

	Propane GMC	Propane W-Star	Diesel Mack
Total Kilometres	185 000	158 000	500 000
Fuel Economy (L/100 km)	98	91	45
Fuel Capacity (L)	635	885	1000
Estimated Range (km)	650	975	2210
Oil Economy (km/L)	1110	2470	330

Table 3/ Summary of Operating Results

Relative mileage accumulation of the three tractors is shown in Figure 12. Relative oil consumption of the three tractors is illustrated in Figure 13.

The shape of the oil consumption curves indicates a definite break-in curve for the propane engines. This is represented by relatively high initial consumption, followed by a gradual levelling off to a relatively constant figure. Engines appear to be broken in by approximately 100 000 service kilometres (62 137 miles). The diesel oil consumption curve was almost perfectly flat at 330 km/L (233 mpg).

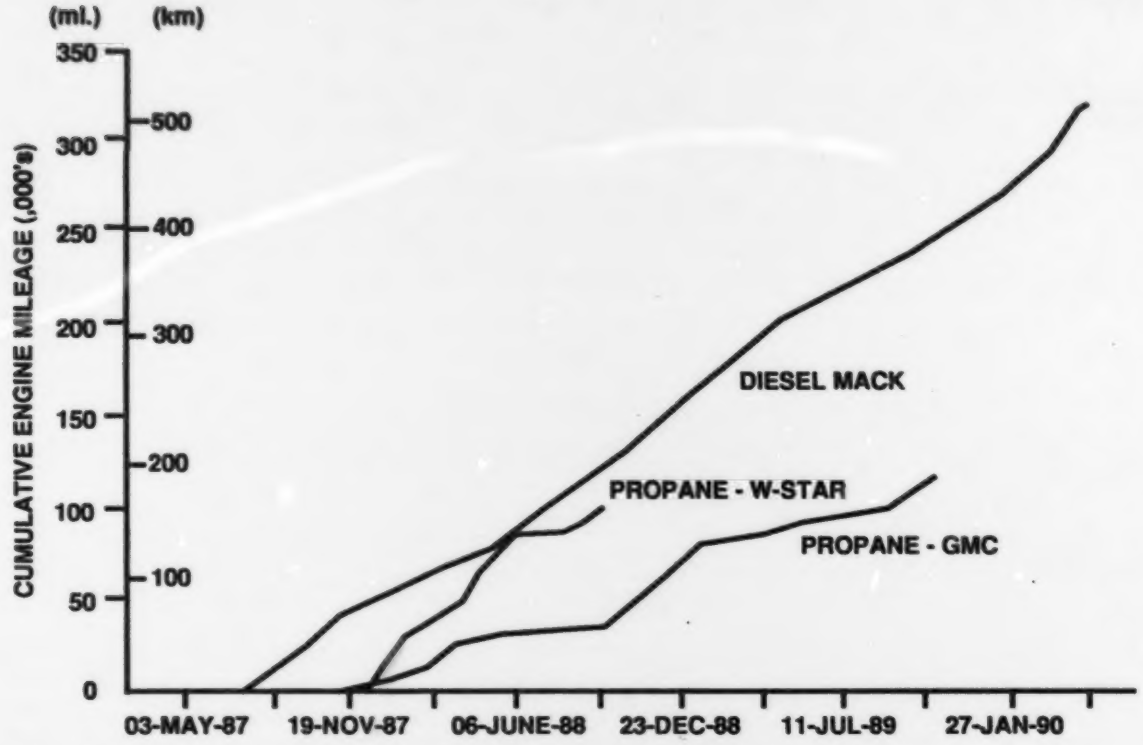

Figure 12/ Cumulative Mileage of Diesel and Propane-powered Tractors

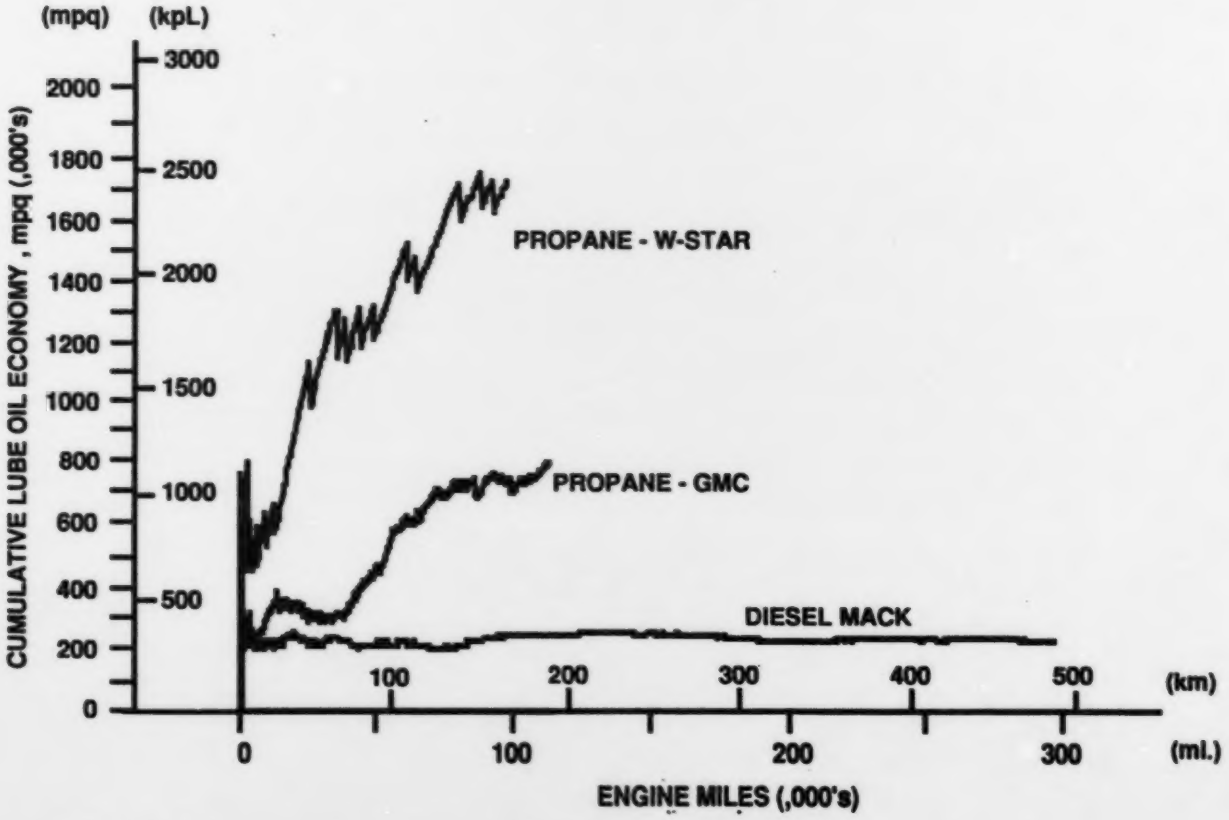

Figure 13/ Oil Consumption of Diesel and Propane-powered Tractors

The considerable differences in oil consumption between the three engines could not be explained. The propane engines were expected to consume oil at a greater rate due to higher intake manifold vacuum. None of the engines were equipped with valve guide seals, however both propane engines were fitted with "umbrella"-type oil spray deflectors, to reduce oil impingement on valve stems.

Inadequate cooling capacity resulted in high temperature engine operation at full trailer loads on grades. Downshifting was required on warmer days to increase fan and water pump speed, dissipating more heat. During the program the cooling systems of both propane-powered tractors were continually upgraded in an attempt to overcome the problem. Larger diameter, coarser pitch cooling fans, and radiators with increased numbers of rows were fitted to both tractors.

The water cooled exhaust manifold, while protecting the turbine, introduced a considerable heat load into the cooling system. An investigation into the use of a standard dry exhaust manifold, to reduce cooling system load, was performed. Exhaust manifold temperature at the turbine inlet was measured with an optical pyrometer. With the water-cooled manifold, the maximum temperature was 677°C (1250°F), however with the dry manifold, the temperature soared to 954°C (1750°F).

Air/fuel mixture was also leaned as much as possible without sacrificing driveability, in an effort to lower exhaust temperature.

It was observed that under turbo overboost conditions (i.e. greater than 69 kPa or 10 psig) the engine had a much greater tendency to backfire – generally under rapid throttle operating conditions. Solutions to the backfire problem would include a reduction in valve overlap, and better boost control.

Both propane engines proved to be very reliable. Problems generally occurred with accessories and conversion hardware. The problems that arose most frequently are described, as follows:

- Missing, due to poor connection of ignition wires into spark plug connector probes, and inadequate insulation between probe and spark plug adapter insert (especially after spark plug replacement);

- Transient boost peaks due to rapid throttle closing resulted in occasional blow-off of air delivery hoses and damage to aftercooler;

- Loss of tension in springs on intake manifold pressure release caps over a period of time due to occasional engine backfiring, resulting in low boost and inadequate power.

This project was completed in December 1989, and both propane engines have now been removed from the tractors. Future work will involve refinement of several systems (described below), re-tuning of the engines, and further in-service road testing of completed engines.

FURTHER DEVELOPMENT

A number of refinements should be made to the propane engine in order to improve reliability to a level comparable with the diesel engine.

Most important is the development of a turbocharger with a heavy-duty wastegate. A wastegate would replace the second throttle plate and boost pressure controlled actuator, eliminating problems associated with pressure surges in the aftercooler and associated ducting.

It is probable that a wastegate would also cure intermittent backfire, caused by transient overboost conditions. It may then be possible to operate satisfactorily with the original diesel intake manifold.

A new spark plug probe assembly was developed late in Phase II, which incorporated a nylon probe and which appeared to solve the problems noted in obtaining a positive, well insulated connection between the distributor and spark plugs. Further testing, and possibly additional development work, should be performed to ensure that this problem has been solved.

While the distributor-type ignition system was reliable, a distributorless, six-coil ignition system would eliminate the need for a distributor adapter on the rear of the air compressor, and a source of routine maintenance (i.e. rotor, cap, bushings).

The Bosch mechanical governor worked very well. However, considerable effort is required to adapt it to operate properly at 100% engine speed. It also requires a drive adapter, which adds to the complexity and cost of the engine. An electronically controlled governor would be simpler to install, possibly at a lower cost.

Propane engines have the potential to meet the strictest US particulate emission standards, as well as those for CO, HC, and NOx standards. However, realization of this potential will require refinement of the engine and its accessories as well as the development of a suitable catalytic converter. In this process, the engine has to be subjected to the EPA transient engine dynamometer test.

CONCLUSIONS

The development and demonstration of propane-fuelled heavy trucks was a success. Over a total of 36 truck months and 350 000 km (217 480 mi.), the two propane engines provided reasonable reliability and fuel efficiency. Engine power was comparable to or better than that of the diesel engine as were engine noise and vibration.

Weaknesses were identified in the turbocharger, ignition, and cooling systems, however these problems may be readily corrected with current technology.

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